FOREST FIRE RETARDANT RESEARCH

A STATUS REPORT

Charles W. George
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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION

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ABSTRACT

Forest fire retardant research was divided into five different study areas: (1) retardant effectiveness; (2) retardant physical properties; (3) retardant delivery systems; (4) retardant-caused corrosion; and (5) retardant environmental impact. Past research is reviewed for each study area; current and future research needs are described.

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CONTENTS

INTRODUCTION

One method of attacking wildland fires involves aerial or ground delivery of water or fire retardant chemicals directly on or ahead of the fire in an attempt to slow or contain it. Fire control agencies in the United States use approximately 20 million gallons of retardant annually in the suppression of wildfires. The cost of the fire retardant chemical exceeds $5 million. Costs associated with the delivery and application of this chemical run the total to approximately $25 million annually. Because such large quantities of chemical are being used and the costs involved in delivery and application are high, potential savings could be realized by increasing the effectiveness of the chemical, and improving methods of delivery, application, strategy and tactics, and through the use of operational guidelines.

In this report, the terms "delivery" and "application" refer to the interactions between the retardant and the fuel complex on which it is used. The tactics and correct placement of retardant by aircraft or by a nozzleman are presently considered to be related primarily to experience and training. The actual tactics are only superficially discussed in this report, but many of the study results can be used in determining the most effective retardant use.

Data from past research (reviewed in each Research Summary section of this paper) have helped to develop standards for retardant performance in laboratory comparison tests and related performance in operational use. Developments in aerial delivery systems have been limited to speculative changes rather than those based on quantified criteria and objective testing. This report summarizes studies that have been conducted to determine the retardant chemicals and delivery systems that would best aid in controlling wildfires. Current and future studies (reported in the Current Research sections) will determine the chemical-physical retardant properties that will optimize retardant delivery and distribution within the fuel complex as a function of the fuel, the fire situation, environmental conditions, and other influencing factors. Figure 1 shows the parameters that must be quantified and considered when formulating retardant use to specific needs. Some knowledge of these parameters is being used now, but as more data are available, understood, and correctly applied, fire managers will be able to correctly choose both the fire retardant formulations and the dispensing mechanism to provide the safest and most effective fire attack system.

Current research at the Northern Forest Fire Laboratory has been organized into five different study areas: retardant effectiveness, retardant physical properties, retardant delivery systems, retardant-caused corrosion, and environmental impact. Numerous interrelated studies are being conducted within each subject area through in-house projects, by cooperative efforts with other Federal and State agencies, and by contractors. These studies will provide much of the data needed, as shown in figure 1, to ultimately tailor retardant use to specific needs. Continued testing of products will aid in upholding quality standards and screening new materials as they are submitted for approval.

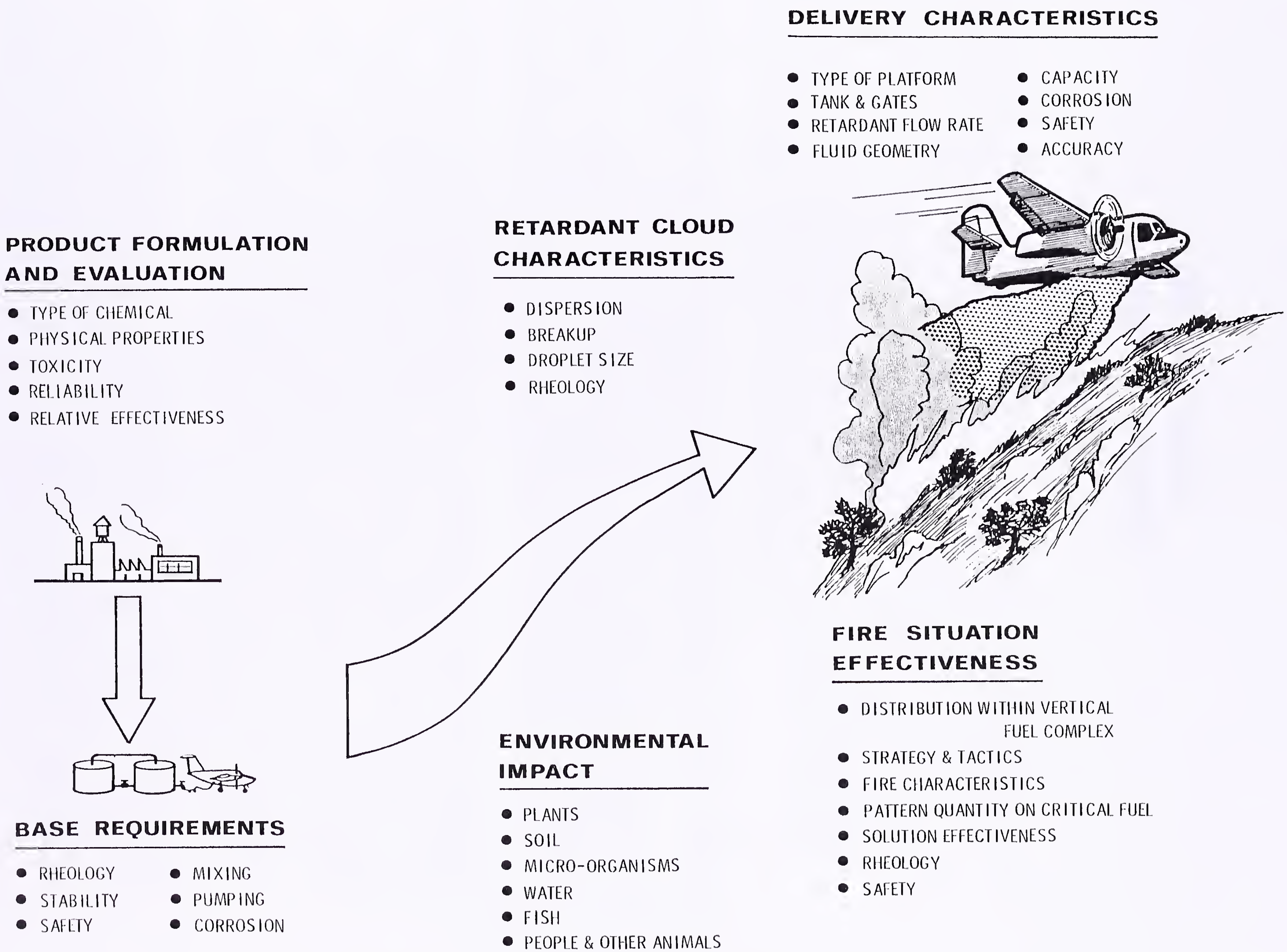

Figure 1.--Parameters influencing retardant effectiveness.

RETARDANT EFFECTIVENESS

Research Summary

Barrett (1931) conducted one of the first documented studies to determine the feasibility of using water-containing chemicals to extinguish or retard wildland fires. Real interest did not develop, however, until Truax (1939), utilizing his experience with fire retardant treatments for reducing the flammability of lumber, conducted laboratory tests with water solutions of chemicals to determine their fire extinguishing ability on flaming and glowing combustion. Finding that some chemical solutions were far superior to water for extinguishment, Truax conducted field evaluations of the most promising chemicals on various types and arrangements of natural fuels. Results of the tests indicated that the retardant effectiveness of the chemical depended upon the type of chemical, its concentration, the rate of application, the fuel type and arrangement, weather conditions, and fire characteristics. Of the various chemicals tested, ammonium phosphate was found to be the most effective.

Tyner (1941) verified the results of Truax and expanded studies to include investigations of synergistic effects of various combinations of chemicals. For the chemicals and mixtures evaluated, significant synergistic effects were not identified.

Other additives, such as wetting agents, to increase the effectiveness of water have been investigated in numerous studies (Fons 1950; Fry 1951; Miller and Wilson 1957; Phillips and Miller 1959; and Davis and others 1961). Although many of these additives increased the water retention or penetration, neither treatment improved the extinguishing or retarding ability of water to the extent attained by the addition of ammonium phosphate compounds tested earlier.

During Operation Firestop (1955a), tests were conducted that considered aspects of chemical effects on the ignitibility of fuels and on the intensity of fires in partially treated fuels. A misunderstanding of retardant action on ignitibility caused investigators to incorrectly conclude that sodium calcium borate was the best firefighting chemical. In these tests, ammonium phosphate compounds actually caused cellulosic fuels to ignite at lower temperatures than water-treated or untreated fuels. The investigators did not, however, consider that ignition sooner and at lower temperatures did not necessarily mean that combustion would be sustained when external heat was reduced. (This fact was shown in later studies of the effect of ammonium sulfate and phosphate on the pyrolysis and combustion of cellulose by George and Susott [1971].) The Operation Firestop retardant studies led to operational use of chemicals that owed their effectiveness primarily to physical properties providing greater or longer moisture retention.

New interest in ground application of chemicals on cellulosic fuels stimulated the Syracuse University Research Institute to conduct comprehensive studies on the effects of water additives on the extinguishing efficiency of water (Aidun 1960). The studies demonstrated that viscous water was about four times more efficient than plain water in extinguishing certain types of laboratory fires. Fires extinguished with viscous water were also less apt to rekindle than those extinguished with plain water. These results were operationally verified during field tests and operational use of viscous water and algin gel (Davis and others 1962).

During laboratory tests to evaluate the effectiveness of forest fire retardants on controlled open burning fires, it was determined that thickened ammonium phosphate, ammonium sulfate, and sodium calcium borate were most effective in reducing the rate of fire spread, radiant energy flux (intensity), and convection column temperature (Hardy and others 1962). The effectiveness of each chemical was a function of the type of chemical and fuel dryness, fire intensity, and environmental conditions. While carefully controlling the dryness and environmental conditions, Rothermel and Hardy (1965) found that all the tested viscous retardants had similar drying rates. Those retardants containing ammonium sulfate or ammonium phosphate chemicals, however, were effective even after their moisture had evaporated.

In a study to relate retardant effectiveness with vertical distribution, Swanson and Helvig (1973, 1974), under contract to the Forest Service,[1] developed a vertical fuel coverage model as a method of providing estimates of the vertical fuel distribution on required retardant quantities. The model views the vertical fuel structure as a series of geometrical segments each described in terms of measured fuel parameters, i.e., geometry, surface area, and volume. The model allows retardant to enter vertically, pass through each fuel segment, and be captured or retained until the surface is saturated. The model was developed on the basis of forest hydrological and retardant dispersion studies (Anderson 1974, Grah and Wilson 1944, and Leonard 1967) and can be calibrated for materials with specified rheological properties. Thus the model can be used to study the effect of various retardant characteristics including film thickness, salt content, fuel type, and the amount of retardant applied to the top of the fuel structure.

George and Blakely (1970) pointed out that in test fires to evaluate the effects of retardant chemicals applied to mat-type fuel beds, the chemicals may have similar effects on rate of spread but different effects on rate of energy release. Because fire retardants are used to reduce both fire spread and combustion rate, it was concluded that both parameters must be considered in effectiveness evaluations. To determine the effects of retardant chemicals (ammonium phosphate and sulfate) on overall fuel flammability, George and Blakely (1972) burned treated ponderosa pine needle and aspen excelsior fuel beds with various amounts of chemical in an environmentally controlled wind tunnel. Results showed that the effectiveness was related to the type of chemical applied (its effectiveness depending on its thermal behavior characteristics and thus availability) and the distribution of the chemical within the fuel bed.

Applying the Rothermel spread model (Rothermel 1972) and using retardant effectiveness data (Rothermel and Philpot, in press), Swanson and Helvig (1973, 1974) also evaluated the effect of application concentration on fire spread. By converting the spread rate to Byram's intensity scale (Byram 1959), the reductions in intensity (knockdown) offered as a function of the amount of retardant applied can be estimated for several fuel situations. The Swanson-Helvig model utilizes the state-of-the-art in fuel description, rate-of-spread modeling, and determinations of retardant effectiveness. Refinement and verification of this model, however, will be required to incorporate retardant types, rheological properties, type of application (extinguishing or retardant action) as a function of the critical fuel, and other fuel and fire characteristics.

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[1]Contract 26-2888 by the Intermountain Forest and Range Experiment Station, Northern Forest Fire Laboratory, to Honeywell, Government and Aeronautical Products Division.

Current Research

Laboratory and field studies are underway and are planned that will refine and verify the Swanson-Helvig model by providing estimates for retardant requirements as a function of the type of fuel, fire, and method of application. The studies will quantify retardant effectiveness in several specific fuel types (grass, brush, timber, etc.) and fire situations. The effects of retardant distribution within the fuel complex will be determined through both laboratory and field tests.

Model inputs will be expanded to consider retardant effectiveness as a function of the mode of attack; i.e., quantify "extinguishing" and "retardant" effects separately and in combination and quantify the importance of retardant rheological properties in both operation modes. The final output will define retardant requirements as a function of the critical fuel in terms of optimum distribution for various fuel and fire situations so that the retardant chemical and rheological properties can be tailored for specific needs.

Continuing studies are evaluating the combustion retarding effectiveness of newly submitted retardant formulations according to qualification and evaluation procedures as outlined in current Forest Service specifications.

Laboratory studies will be conducted in cooperation with the fire retardant manufacturers and other research units at the Northern Forest Fire Laboratory. National Forest Systems, Bureau of Land Management, State fire management agencies, and the San Dimas Equipment Development Center (USDA Forest Service) may be involved in the field tests.

RETARDANT PHYSICAL PROPERTIES

Research Summary

For centuries, water has been used to extinguish fires on wildlands and in urban areas. Not until recently have chemicals been added to enhance the fire retarding and extinguishing qualities of water. Potential fire retardant chemicals were tested at the Forest Products Laboratory (Barrett 1931; Truax 1939; Tyner 1941) to improve the chemical effectiveness of water, but little was done to improve its physical properties.

With the advent of the operational use of aircraft for cascading fire retardant, it was apparent that considerable effort was warranted to alter the physical properties of the retardant in order to improve the delivery or drop characteristics and increase retardant retention on aerial fuels--especially when high winds and extreme drop heights were encountered, as often occurs in mountainous terrain and in difficult fire situations.

Miller and Wilson (1957) tested the use of a thickened sodium calcium borate as a suppressant and retardant for ground application and for aerial delivery. The drop characteristics of borates appeared superior to those of water. Borate had better coating and water-holding ability and seemed to have some long-term retarding effects. Disadvantages of borate were its corrosiveness, abrasiveness, toxicity to plants, and its difficult handling properties.

Davis (1959) showed the advantages of viscous water during drop tests of water and thickened water in comparative efforts to determine which gave the best ground distribution patterns and coverage on forest fuels. Phillips and Miller (1959) evaluated bentonite clay as a viscous agent and found that under severe drying conditions it did not remain effective as long as borate. However, they did note several operational advantages: bentonite weighed less, was cheaper, was less corrosive and abrasive, was nontoxic, and had drop characteristics similar to borate.

Johansen and Shimmel (1963) performed tests on and initiated the operational use of industrial gums and attapulgite clay as thickeners for water solutions of monoammonium phosphate and diammonium phosphate fire retardants. The thickened retardant solutions gave more concentrated ground distribution patterns and resulted in more retardant salt per unit area covered.

Aidun and Grove (1961), working for the Bureau of Yards and Docks, Department of the Navy, tested water thickened with industrial gums and bentonite clay and reported a marked increase in the fire knockdown or suppressing ability of thickened water. These results stimulated forest firefighting agencies to initiate further studies to determine the feasibility and possible advantages of adding gums and gels to water and water-chemical solutions for both ground and aerial application.

Davis and others (1962, 1965) tested water thickened with gels and gums on forest, range, structural, and vehicle fires and found that much more plain water than viscous water was needed for the same extinguishment job. On one vehicle fire, plain water was having little extinguishing effect, but thickened water put the fire out. Trout (1970) and Livingston (1972), working with thickened water for inside building sprinklers, showed the distinct advantage of larger droplets in penetrating the heat column and reaching the base of the flames. Results of these studies indicate that viscous agents which create larger droplets can provide greater effectiveness for ground and aerial applied forest fire retardants when used as extinguishing agents (direct attack situations).

Viscous agents were first incorporated in aerial and ground retardant formulations for the purpose of providing better adherence of the retardant to the fuels and to minimize the runoff. Davis (1959), George and Blakely (1973), and George (1975) recognized several advantages of thickened retardant for aerial delivery: (1) greater shear resistance during breakup; (2) larger mean droplet sizes; and (3) less material lost to drift and evaporation. George and Blakely also noted superior drop characteristics were obtained for gum-thickened retardants as compared to clay-thickened and unthickened retardants.

Recent drop tests[2] conducted at Marana disclosed the importance of retardant rheological properties other than viscosity. Water thickened with guar gums, attapulgite clay, invert emulsion, and dilatants was dropped from the same tank system under similar environmental conditions. Although a variety of viscosities for each material were used (from 1,500 to 10,000+ centipoise for some materials), ground distribution patterns and movies of the drops showed that the gum-thickened retardants were eroded less by shearing forces during exit from the aircraft tanks and during freefall to the ground than the other retardants tested.

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[2]A study of the effects of tank and gating characteristics on retardant ground distribution patterns, Study Plan 2107-17C, unpublished data on file at the Northern Forest Fire Laboratory, Missoula, Montana.

Because of the results from these tests, studies were undertaken to establish the relationship between the rheological properties of a fire retardant and its drop behavior, dispersion characteristics, and wetting-out properties (Andersen and others 1973, 1974a,b).[3] Andersen has developed analytical models to describe the aerodynamic breakup of aerially delivered fire retardant. These models, together with shock tube and gas gun experiments, indicated that the breakup characteristics of liquid retardants are influenced by the effective viscosity. The effective viscosity incorporates effects of fluid viscosity and fluid elasticity at the shear rate specified (effective viscosity is shear-rate dependent). It was shown that for gum-thickened retardants, breakup rate decreases and droplet size increases as the effective viscosity is increased. It was concluded that gum-thickened retardants are generally superior. Their elastic nature allows the maintenance of a high effective viscosity under shear rate conditions experienced during aerial drops. The large apparent viscosity of clay-thickened retardants is so reduced by shear that the resultant drop characteristics are similar to water or unthickened retardant.

Current Research

Laboratory and field tests have shown the importance of retardant rheological properties on the aerial breakup of the retardant and the resultant ground distribution pattern. The retardant rheological properties affect the mean droplet size and thus their velocity, trajectory, and consequently, the fuel wetting or coverage. Although general analytical models were developed to describe the aerodynamic breakup of retardant, the implications and predictions of the models in terms of effect of the many specific parameters on ground patterns have not been completely evaluated. Correlation of predicted and actual dissemination patterns is needed to make the best use of these models and obtain potential improvement by verifying or refining certain constants.

Past studies have also shown that the rheological properties of retardants have significant effects on fuel wetting by dynamic droplet impaction and on subsequent liquid storage by the fuel. Further studies are needed to develop analytical models that elucidate the important impact and fluid properties for impaction wetting and static film spread and storage within the vertical fuel complex.

Development and verification of models describing aerial breakup and retardant distribution within the vertical fuel as a function of retardant chemical-physical properties (including rheological properties) will provide the tools necessary to tailor the retardant to specific drop conditions and fire situations. The tailored formulation may be one based on trade-offs between optimum delivery characteristics and optimum distribution within the fuel complex or it may define a system allowing preselection of retardant properties for the conditions encountered.

Studies are presently being conducted (contract to Shock Hydrodynamics) to determine the retardant rheological properties affecting aerial breakup, formation of the retardant cloud, and resulting distribution within the fuel complex; i.e., those fuels considered most critical. These data will help to correlate rheological properties to droplet size distribution and actual dispersion patterns formed. Other studies are continuing to quantify the rheological properties of currently used retardants under the range of shear conditions encountered in actual retardant drops. Future studies will evaluate the effect of varying retardant rheological characteristics on distribution and retention in representative fuels.

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[3] Contract 26-3198 by the Intermountain Forest and Range Experiment Station, Northern Forest Fire Laboratory, to Shock-Hydrodynamics, Division of Whittaker Corporation.

RETARDANT DELIVERY SYSTEMS

Research Summary

Shortly after World War I, forest fire control agencies began to use aircraft for aerial patrol. In 1935, attempts were made to apply water to forest fires from a Ford Tri-motor by means of 8-gallon beer barrels, steel cans, and through a hose trailed behind the aircraft. Results of these and other tests (Headly 1943) were not promising and testing was not resumed until 1947. Hanson and Tebbe (1947) reported using P-47 and B-29 aircraft to drop exploding containers filled with water. Although partially successful, the system was discarded because of the danger to ground personnel.

In 1953, water was first freedropped, using a DC-7 tanker with a 2,400-gallon water-ballast-dump system (Operation Firestop 1955b). The test showed the practicality of cascading fire retardant on wildland fires. Also, during Operation Firestop, a 600-gallon tank was installed in a TBM and water was cascaded to determine ground pattern distributions. The patterns indicated adequate concentrations were attained and led to two successful drops on test fires.

The Firestop tests marked the beginning of the operational use of aerially delivered fire retardants. In 1956, Stearman aircraft with 150-gallon spray tanks and emergency dump doors were used successfully to cascade over 150,000 gallons of water and retardant on fires (Davis 1959). Since that time, many different types of aircraft have been equipped with tanks having up to 4,000 gallons capacity and have been used operationally with various degrees of success. The tank and gating systems in these aircraft, however, have remained essentially the same as those on the first TBM. Limited refinements have been made in the systems, mostly for safety or economy. Until recently, few attempts have been made to relate the tank configuration and door opening system to ground patterns.

Perhaps the most significant advance in retardant release systems has been the development of a pressurized dispensing system by Food Machinery Corporation under an Air Force contract (USAF 1973; George 1973). The pressure system is modular and is constructed so that it can be quickly loaded into a C-130 aircraft (presumably an Air Force, National Guard, or Reserve aircraft). The pressure system permits close regulation of flow rates, thus allowing patterns to be altered to meet specific fire situations.

MacPherson (1968) developed a theoretical model to estimate the width of the wetted area and to produce idealized contour patterns of retardant drops. His model predicted ground distribution patterns based on aircraft speed and altitude, tank geometry, door opening speed, and certain parameters of the retardant breakup process.

Static tests (flow rate) and aerial drop tests conducted by the Northern Forest Fire Laboratory (1973, 1974) indicated that the tank geometry, door opening size and speed, and venting affect retardant flow rates from the tanks and thus influence ground distribution patterns. The studies showed that patterns can be improved by designing the release system to minimize shear and breakup and by controlling retardant flow rates from the tank.

A contract was let to Honeywell Corporation (Contract 26-2888) to quantify critical parameters that can improve aerial delivery of retardants. Results of this contract (Swanson and Helvig 1973) indicated that the most efficient method of delivering retardant was by the conventional cascade method (other systems--containerized

delivery, solid retardant [ice, etc.] were investigated). Utilizing analytical models of liquid breakup, the MacPherson model, and ground distribution patterns from previous quantified tank and gating systems, Swanson and Helvig developed an empirical retardant dispersion model. The model predicted ground distribution patterns as a function of tank and gating system parameters and aircraft drop height and speed. With few exceptions, correlations of predicted and actual retardant flow rates and ground distribution patterns for various tank and gating systems revealed that if the retardant flow history from the tank is known it is possible to predict ground distribution patterns with reasonable accuracy.

Swanson and Helvig's model does not deal with the effect of fluid geometry and the addition of individual tank increments dropped either simultaneously or in sequence. To obtain the data required to incorporate the effects of fluid geometry, drop spacing, and retardant rheology, and to further refine the model, Swanson and Helvig recommended that these parameters be studied independently and the results applied to designing optimum tank and gating systems for specific aircraft and for specific fire situations.

Current Research

Research has shown that the retardant flow rate from the tank and rheological properties govern the retardant breakup, cloud formation, and ground pattern. Quantification of parameters influencing the flow rate and breakup will make possible the refining of models so that performance guidelines and tank and gate design specifications can be written. The information needed will be gathered and utilized as follows:

1. Static testing of drop systems to quantify flow rates, door opening histories, and tank geometry, and to relate these data to deformation, breakup, dispersion, and ground patterns.

2. Develop and test an experimental tank and gating system (ETAGS) for determining the effect of tank and gating parameters, such as door opening speed, tank geometry, venting, clutter, exit areas, compartment separation, and retardant quantity.

3. Design, fabricate, test, and install an optimum tank and gating system (based on information gathered from the test of the experimental tank and gating system) in an appropriate aircraft; perform drop tests and then an operational evaluation. Tank construction costs may be developed from this study.

4. Use data from static testing to model responses of drop patterns to drop height, airspeed, and type of retardant. Prepare user guidelines outlining the most effective use of existing air tankers in given situations.

5. Define the optimum tank and gating system for specific fire situations (according to the National Fire-Danger Rating System and Fire Spread Models) and for various aircraft (tank and gating specifications).

6. Develop design information to be used by private contractors when tanking aircraft.

A contract has been let to Honeywell[4] to design, construct, and install an experimental tank and gate system in a Forest Service P2V aircraft. This contract involves a subcontract to Aero Union Corporation, an air tanker contractor, and provides for cooperation with the air tanker industry. In addition, Honeywell currently is contracted by the Forest Service to develop mission guidelines for several selected

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[4]Contract 26-3425 by the Intermountain Forest and Range Experiment Station, Northern Forest Fire Laboratory, to Honeywell, Government and Aeronautical Products Division.

aircraft.[5] Both contracts will provide information that is being utilized by the industry through the National Air Tanker Screening and Evaluation Board (the Board includes user agencies and air tanker contractors) and their established criteria.

Aerospace Corporation is cooperating in the ETAGS study by providing review of design analysis and by conducting structural analysis of critical components and subsystems.

RETARDANT-CAUSED CORROSION

Research Summary

Corrosion induced by retardants in air tankers and ground support equipment has been considered a problem since the very beginning of the retardant program (Operation Firestop 1955a). Retardant formulations without inhibitors were tested in 1964 for stress and fatigue corrosion on several metals commonly used in air tankers. The results showed that the retardants were corrosive in varying degrees, from failures within 2 days to only small pits after a year's time, depending on the retardant-metal combination examined (USDA Forest Service 1964).

After the 1964 fire season, a six-man task force examined a group of air tankers which had been used to carry several different types of retardant and found varying amounts of corrosion damage. The degree of damage was found to be related to the type of retardant carried, the type of metal used in the construction of the aircraft and tanks, the use of protective coatings, and the housekeeping practices of the operators. Methods for reducing the corrosion damage (Davis and Phillips 1965) were recommended. Early in 1968, tests were run on samples of retardants and aluminum alloy 2024-T3, using immersion tests and the Magna Corrater. On the basis of these tests it was recommended that the Magna Corrater be used as a preliminary test for corrosion on any new retardant product (USDA Forest Service 1968).

In 1969, the Forest Service issued specifications for both dry and liquid retardants (USDA Forest Service 1969b, 1970b) that outlined corrosion tests to be performed on aluminum alloy 2024-T3. Although other alloys have been corrosion tested (USDA Forest Service 1968 and 1969a), aluminum alloy 2024-T3 was chosen because it is the most critical material from the standpoint of aircraft safety. Since then, other metals and retardant formulations have been examined for corrosion using the Magna Corrater and other general corrosion rate techniques (USDA Forest Service 1970a; Bradford 1973). The last thorough inspection of equipment in contact with retardants was in 1965. Since that time, new formulations and equipment have come into use. The nature and magnitude of corrosion damage to this equipment must be quantified, including determination of the alloys that are susceptible to corrosion damage and the type of corrosion causing the damage. Laboratory tests can be performed for the various types of corrosion and results of these tests correlated with corrosion determined to be present in the field.

The Forest Service has awarded a contract to Ocean City Research Corporation to assess the corrosion effects of chemical retardant on mixing and delivery systems, particularly air tankers, and to determine the corrosion rates on critical alloys, and correlate these rates to actual field damage and recommend methods of reducing the corrosive effects (Contract 26-3250). By inspecting aircraft and reviewing

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[5]Contract 26-3332 by the Intermountain Forest and Range Experiment Station, Northern Forest Fire Laboratory, to Honeywell, Government and Aeronautical Products Division.

literature, the contractor has identified the 10 most common alloys used in air tankers and ground equipment, and the most corrosion-prone portions of mixing, handling, and delivery systems. Ten alloys and five retardants were tested for general corrosion rates by weight loss and linear polarization methods utilizing constant and alternate immersion exposures. Galvanic corrosion rates for the various metal-to-metal couples in the different retardants were determined. The stress corrosion of the metal-retardant combinations was determined using both U-bend and double cantilever beam methods; alloys that were susceptible to corrosion fatigue have been fatigue tested. The tendency of the alloys to localized corrosion was characterized as was the critical pitting potential at which passivity breaks down and pitting begins. Ten candidate protective coatings were selected and exposed to the retardants for 1 month. The three best coatings were then tested over long-term exposures. From the literature, 10 inhibitor candidates were selected and tested with each of the alloy-retardant combinations; the three most promising inhibitors were selected and subjected to galvanic, stress, fatigue, and general corrosion tests (Ocean City Research Corporation 1974).

Current Research

The corrosive effect of present and future retardant formulations must be controlled within safe and economical limits. Basic knowledge is being accumulated on the extent and types of retardant-caused corrosion. Corrosion problems are being identified by equipment manufacturers, aircraft contractors, or by fire control personnel associated with retardant mixing, handling, and delivery.

Engineers specializing in corrosion abatement are helping to establish general corrosion prevention guidelines. Guidelines may be implemented through design or performance requirements for retardants, mixing, handling, and delivery equipment, and the adoption of better housekeeping techniques.

The basic aim of current corrosion research is to:

1. Develop performance requirements which specify the permissible limits of critical types of corrosion acting on various alloys and performance tests. These performance requirements will be included in the specifications.

2. Design inhibitor systems that will restrict corrosion to permissible limits.

3. Establish user guidelines that cover corrosion-resistant alloys, inhibitors and protective coatings, and maintenance procedures.

Current studies are aimed at evaluating the corrosion characteristics of new retardant formulations on several alloys by means of electrochemical techniques, and examination of aircraft and mixing equipment to determine the extent of the problem, to identify alloys used, and the types of corrosion occurring. Laboratory tests are being conducted to determine corrosion characteristics and to correlate findings with actual damage. Ocean City Research Corporation is performing a major part of the corrosion studies and is preparing recommendations to aid retardant users.

Future studies will determine inhibitor depletion rate for various inhibitors, alloys, and retardant solutions. Inhibitors will be rated for reducing the potential of stress cracking and fatigue susceptibility. Corrosion rates will be determined relative to the type of inhibitor and concentration. Inhibitor combinations or systems will be evaluated to minimize corrosion to those alloys determined to be critical.

Studies will be conducted to correlate the results of corrosion tests using the Magna Corrater and tests for uniform, stress, fatigue, and galvanic corrosion, etc., performed by Ocean City Research Corporation. If a correlation can be obtained, the Magna Corrater will provide a simple method for screening and testing new inhibitor-containing formulations.

RETARDANT ENVIRONMENTAL IMPACT

Research Summary

The effect of forest firefighting chemicals on the environment has been a concern of fire control officials since the beginning of the retardant program. In 1955 when "Operation Firestop" (the program that pioneered aircraft-applied chemical retardant) was initiated, it was recognized that the toxicity of retardants must be tested (Operation Firestop 1955a). Field tests using sodium calcium borate were conducted in 1956 (Miller and Wilson 1957), but the toxic properties of the compound were overlooked in favor of its effectiveness. In 1958, laboratory and field tests of bentonite were undertaken, and the results appeared promising (Phillips and Miller 1959). One of the advantages of bentonite was that it was nontoxic to plants and animals. In subsequent years many other materials were tested, toxicity being a point of concern. In 1960, new materials including several diammonium phosphate (DAP) based formulations were evaluated (Davis and others 1961). The use of DAP formulations was soon followed by ammonium sulfate compounds--both showed many advantages over the previous materials.

Toxicity has not been considered a problem with ammonium phosphate and ammonium sulfate compounds because both materials have been commonly used agricultural fertilizers (Sauchelli 1964). In addition, ammonium phosphates have been used as a source of nitrogen and phosphorus in cattle rations, and where all the supplemental protein was provided through the compound, no adverse effect was found (Bell and others 1968).

Phos-Chek, a DAP-based retardant, was tested on mice and rabbits for skin and eye irritation, and oral toxicity.[6] The results indicated no adverse effects to mice when fed up to 25,000 mg of Phos-Chek per kilogram of body weight. The chemical was found to be only a mild irritant to eyes or skin.

Fire retardants have been accused of causing nitrate poisoning in livestock. A study in 1970 (Dodge 1970) indicated that for retardant to cause nitrate poisoning it must be converted to nitrate by soil bacteria and taken up by plants which must be ingested by the cattle. Dodge also shows that the conversion of ammonia salts to nitrate by plants can happen only under special climatic conditions; the likelihood was less than from range or pastureland fertilization. Other evidence has also indicated that these compounds could fall in a nontoxic category.

Experience with ammonium sulfate and ammonium phosphate fire retardants in the past years has led to skepticism concerning the nontoxic effects of these chemicals, especially in regard to their effects on fish and aquatic life. Although there have been many reports of fish kill during this time, only a few have been documented. In 1966, a trout kill in Sonoma County, California, was reported when some retardant overshot the fireline and dropped into a small creek.[7] During the Swanson River Fire in Alaska in 1969, many salmon were killed near the fire on which nearly a third of a million gallons of retardant had been used.[8] Although retardants have not been definitely tied to the salmon kill, the possibility of retardants being the causal agent cannot be ruled out. The Ukiah California Rod and Gun Club blamed the California

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[6]Monsanto Company. Toxicological investigation of Phos-Chek 202. Report by Younger Laboratory to Monsanto, December 6, 1965, 7 p. On file at Northern Forest Fire Laboratory, Missoula, Montana.

[7]Memo to California State Forester, F. H. Raymond, July 14, 1966.

[8]Memo to Sport Fishing Institute, P. A. Douglas, from Alaska State Director, Bureau of Land Management, 1970.

Division of Forestry for creating a major pollution threat to the Russian River by allowing spillage and waste from a retardant plant to be swept into the river.[9] On February 24, 1970, in excess of 270 juvenile steelhead trout were reportedly killed by a fire retardant chemical. A number of other similar instances of detrimental retardant impact have been documented.

Past experience, then, indicates that fire retardants mainly affect the environment through impact on water quality, and subsequently fish and other aquatic life. With a knowledge of the constituents of currently used fire retardant compounds and a review of the literature, some inferences can be made as to the degree of toxicity of these retardants in relation to certain animals, freshwater fish, and aquatic life.[10]

Because of the complex nature of the problem and the antagonistic or synergistic effect of retardant ingredients, further laboratory tests concerning the threshold levels for the total compound were found necessary.

Three major fire retardant compounds are currently being used throughout the United States. The majority of this retardant (approximately 20 million gallons annually) is applied from fixed-wing aircraft, the remainder from ground tanker units or helitankers, so maximum utilization and control can be achieved. Because it is more likely to reach streams or lakes directly, aerially applied retardant is of primary concern in an evaluation of the effect of retardants on water quality.

Because diammonium phosphate, ammonium polyphosphate, ammonium sulfate, and attapulgite clay make up most of fire retardant formulations, the effects of these specific compounds were studied first.

The literature indicated that many of the ions were lethal to fish and other aquatic life at the concentrations in the undiluted retardant. Obviously, these concentrations will be reduced when these materials are placed in any stream or body of water. The concentrates nevertheless provide a starting point from which to evaluate possible toxic effects.

Because of widely varying test conditions, investigators disagree on the concentrations of retardant chemicals that are lethal to different fish. Only recently have methods of testing the effects of pollutants on fish been standardized. The term most commonly used and approved by fish toxicologists concerning the limiting or threshold levels for various chemicals is TLm, the median tolerance limit, or the amount of chemical required to kill 50 percent of the test species within a specified time, such as 24 or 48 hours. Information taken from various sources but summarized by McKee and Wolf (1963) as to the toxic levels (TLm) determined for specific ions and under given conditions for fish and other aquatic and marine life indicates that the threshold concentration for ammonia is many times lower than for any of the other components.

Studies by the National Marine Fisheries Service (Blahm and others 1972, 1974) supported these conclusions and have shown that the 24-hour TLm for Coho salmon and rainbow trout of varying ages are from 128 to 1,760 milligrams per liter of retardant depending upon the type of retardant, the pH of the water, and the age of the fish. The toxicity of each retardant was directly correlated with the concentration of the free ammonia (NH_3) in the retardant, which in turn was dependent upon the amount of ammonia (NH_4^+) contained in the retardant and the pH of the solution.

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[9]KXTV News, September 18, 1970; and memo to Department of Fish and Game from Director, Department of Conservation, Resources Agency of California, September 8, 1970.

[10]C. W. George, 1971. Partially completed literature review on the environmental impact of fire retardants. Unpublished report on file at Northern Forest Fire Laboratory, Missoula, Montana.

A study by the Bureau of Sport Fisheries and Wildlife using total retardant formulations has similarly shown that ammonia is the critical toxic component of the formulations for certain invertebrate aquatic organisms (freshwater shrimp) and egg-sac fry of Coho salmon and rainbow trout.[11]

Van Meter and Hardy (1975) developed a method of estimating the elapsed time or travel distance necessary for retardant to be diluted to nonlethal concentrations for a given size stream and amount of retardant. As more complete data on the toxicity of various retardants and their components become available, the effects of retardant on water quality and stream chemistry can be estimated with greater precision.

Current Research

A literature review and past experiences indicate that retardants can have a detrimental impact on water quality and aquatic life. The primary ingredient in current fire retardants responsible for this impact has been identified as ammonia. It is unlikely that effective and economical substitutes will be found, in the immediate future, for the ammonium fertilizer compounds currently being used in retardant formulations. Further studies quantifying impacts on the forest environment with emphasis on water quality are necessary to determine trade-offs between fire effects and retardant effects.

For retardant falling directly on surface water, Van Meter and Hardy have developed some relationships to permit calculating lethal concentrations and residence time. Retardant falling on hillsides away from streams will interact with the soil, thus individual components will travel at different rates. Components that reach a stream change organism communities, depending on concentrations, duration, and chemical form.

More in-depth studies are being conducted to quantify the entry, fate, and impact of fire retardants in and alongside forest streams. A cooperative study with Pacific Northwest Forest and Range Experiment Station is being conducted to determine the short- and long-term effects of parallel and cross-stream retardant drops on water quality, fish, and benthic organisms.[12] Concurrently, information will be gathered on leaching of retardant chemicals and their effects on plants and forest soils. Data will include the relative mobility of the various retardant chemicals due to leaching, overland flow of retardant chemicals during intense storms, and the effect on the mobilization of mature soil nutrients.

Other studies will determine the dilution rates of retardants dropped into various sized streams. Retardant concentrations will be a function of time after stream entry and the distance downstream from point of entry. Data will be gathered on the impact of retardants on aquatic life by measuring the initial concentration of retardant introduced into a stream and the effect of the retardant "slug" as it moves downstream and becomes diluted.

Continued studies and evaluations are being made to determine the toxicity of new fire retardants submitted for qualification under USDA specifications.

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[11] H. O. Sanders and W. W. Johnson, 1974. Bureau of Sport Fisheries and Wildlife, Fish Pesticide Laboratory, Columbus, Missouri. Unpublished report on file at Northern Forest Fire Laboratory, Missoula, Montana.

[12] Study Plan 1602-54 "A plan for a study of the effects of streamside application of ammonia-based fire retardant on streamwater chemistry and benthic organisms." C. Hawkes and L. Norris, Pacific Northwest Forest and Range Experiment Station (4/74). Norris and others, "Progress report on the entry, fate, and impact of fire retardants in forest streams." Pacific Northwest Forest and Range Experiment Station (2/74).

Data from current studies will be used in future studies to evaluate trade-offs between environmental effects of fire and the use of retardants.

SUMMARY

The flow chart in figure 2 summarizes the many parameters that must be quantified and considered to prescribe retardants for maximum effectiveness in specific situations and with optimum safety.

The retardant research program at the Northern Forest Fire Laboratory has been divided into five study areas: effectiveness, physical properties, delivery systems, corrosion, and environmental impact. Within each study several substudies are being performed in-house, by contractors, and in cooperation with other agencies. Figure 3 shows the time lines for studies planned for the next 5 years and the organization that will conduct each study.

Retardant effectiveness studies are designed to determine the optimum amounts of chemical required to penetrate and coat the critical elements of the fuel complex and retard or extinguish flaming and glowing combustion.

Examination and quantification of the physical properties of retardant formulations provide data that define the effects of retardant rheological properties on aerial breakup and resulting distribution within the fuel complex. The data are also used to correlate and formulate retardants to specific needs.

Research to quantify the effects of wind, tank and gating parameters, and drop height and speed on the deformation, breakup, dispersion, and final ground distribution patterns is providing criteria to design tank and gate systems for specific needs and for more effective usage by operating personnel.

Corrosion problems have been identified by equipment manufacturers, aircraft contractors, and fire control personnel associated with retardant mixing, handling, and delivery operations. Types of corrosion, the causes, and methods for minimizing the damage are described. Studies are continuing to quantify the effects of combinations of inhibitors, the effective lifetime of inhibitors, and the causes of various kinds of corrosion and how it can be minimized.

Studies indicate that ammonia is the retardant agent toxic to stream life. The extent to which fish and other organisms are affected is determined by the residence time of high ammonia concentrations. Lethal levels vary greatly and are related to fish species, age, and size. Continued research is quantifying impacts on forest flora, soils, fish, and other organisms so that the environmental effects of fire can be weighed against the impacts of retardants.

Cooperators and contractors participating with the Northern Forest Fire Laboratory in the studies are: Pacific Northwest Forest and Range Experiment Station; National Forest Systems; Bureau of Land Management; National Marine Fisheries Service; California Division of Forestry; Honeywell Corporation; Aerospace Corporation; Aero-Union; Ocean City Research Corporation; and Shock Hydrodynamics Corporation.

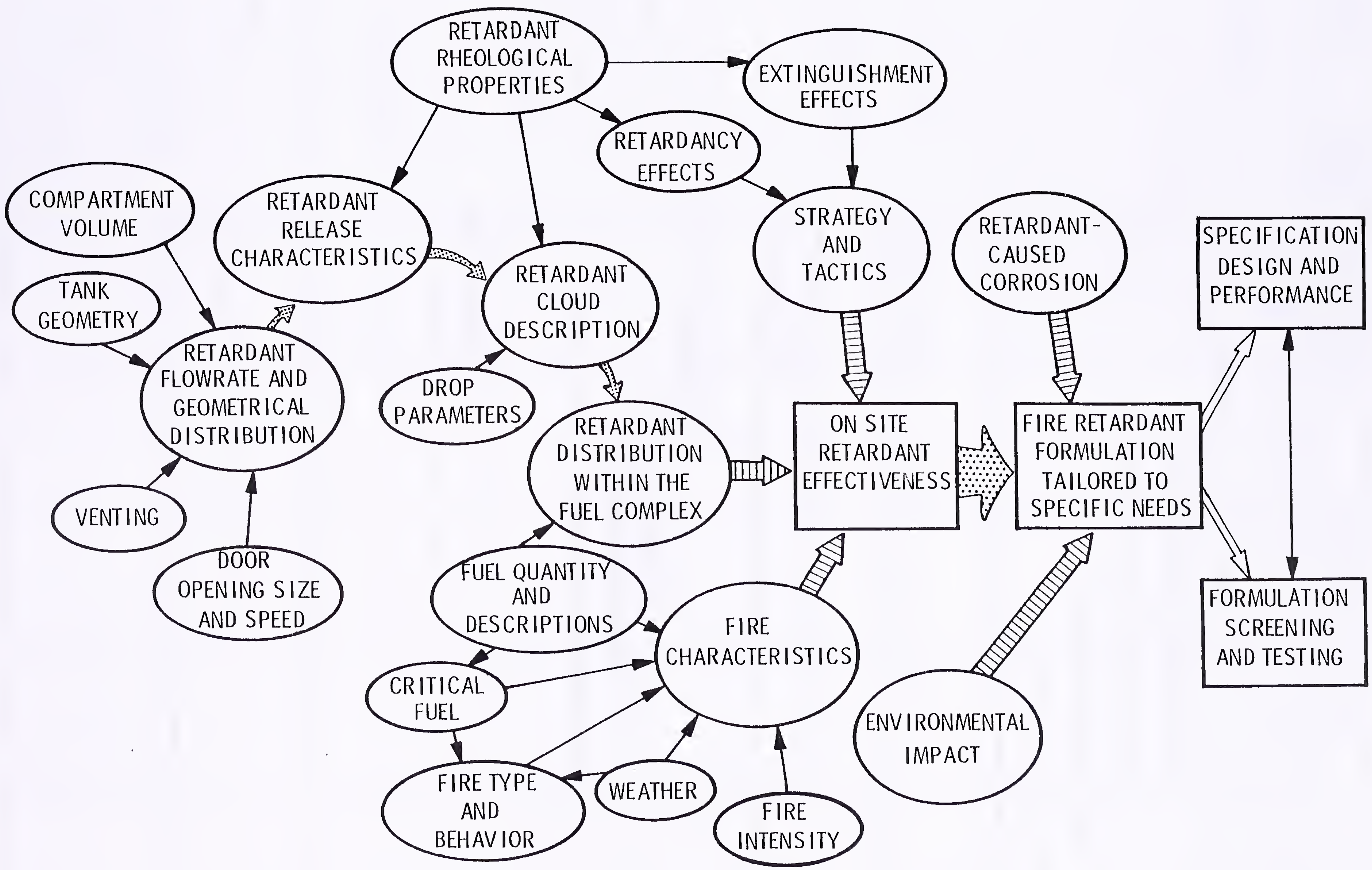

Figure 2.--Integration of studies.

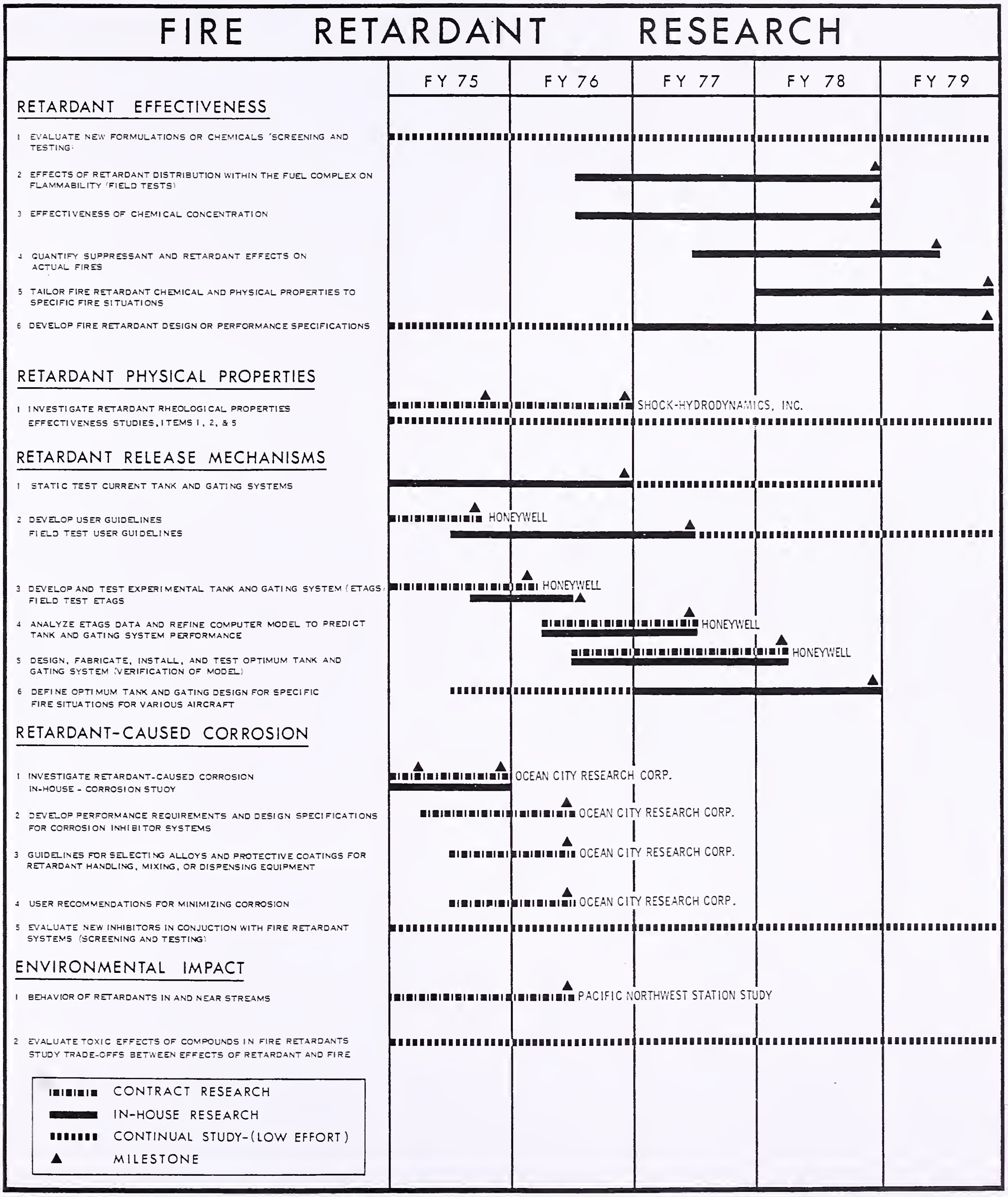

Figure 3.--Fire retardant research time line.

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Forest fire retardant research was divided into five different study areas: (1) retardant effectiveness; (2) retardant physical properties; (3) retardant delivery systems; (4) retardant-caused corrosion; and (5) retardant environmental impact. Past research is reviewed for each study area; current and future research needs are described.

OXFORD: 432.2, 432.331.
KEYWORDS: fire retardants, rheology, corrosion, air tankers, aerial delivery systems, environmental impact, safety, evaluation.

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